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Adding biochar to the composting process: effect of the resulting amendment in agricultural soils

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CONTENTS

0. SUMMARY

Agricultural soils are reaching critical points in soil health and functionality. The main soil issues are loss of structure, low fertility and soil carbon deficits. Previous experiences support that mixing compost and biochar and using the mixture as soil amendment can improve plant growth by increasing water and nutrient retention and decreasing soil compaction and, in addition, being a sustainable option were residues are reused and C sequestrated in soils. Moreover, some recent studies go further and suggest the application of biochar in composting process.

In our study, a review of the effect of applying co-composted biochar in agricultural soils was done. Nineteen worldwide articles studying soil and plant parameters as soil organic carbon, soil water content, pH, cation exchange capacity, greenhouse gases emission, plant nutrient uptake and plant yield, were reviewed.

Co-composted biochar (COMBI) application in soils generally resulted in beneficial changes for soil health as an increase of soil organic content, soil water content, cation exchange capacity (especially when applied in high doses), crop yield and a reduction in N_2O emissions. Moreover, co-composted biochar as amendment also regulates soil pH in the correct range between 5.5 and 7.5. Regarding CO_2 emissions, different trends were observed among reviewed studies and more investigation needs to be done to study soil CO_2 emissions together with other emissions produced in the whole life of co-composted biochar and compared with those emissions that biomass would have emit if was not converted into this material. All these trends greatly vary with different experimental conditions as soil type, soil pH and COMBI application rates.

Finally, further work on the application of co-composted biochar in soil quality and plant growth is still necessary to understand the effect of co-composted biochar when applied in different conditions as soil type, soil pH, location, amendment application rate, among others.

Keywords: co-composted biochar, soil quality, plant growth, sustainability

1. INTRODUCTION

1.1. Agricultural soil health: Current situation and suggested practices

Soils are fundamental for life on Earth, since food production, animal and plant species, air renovation and public health depend from this resource (López, 2013). This ability of soils to function as a biodiverse organism that sustains life in earth is called soil health (USDA-NRCS, 2019). Soil health depends on physical, chemical and biological issues as absence of sealing, erosion, compaction, soil nutrient mining, salinization and pollution. These are evaluated using Soil Health Indicators: nutrient availability, workability, oxygen availability to roots, nutrient retention capacity, toxicity, salinity and rooting conditions (Global Soil Health, FAO; Jian, 2020).

In addition to soil health, soil quality is another concept that is gaining recognition around. Soil quality and soil health are not the same concept and they have different meanings. According to United States Department of Agriculture (USDA-NRCS, 2019), soil quality is the capacity of a soil to function, within its natural or managed ecosystems, to sustain productivity, enhance water and air quality, support human and animal health, and habitation.

Human pressures on soil resources are reaching tipping points in soil health, specifically, according to "Status of the world's soil resources" report from the Food and Agriculture Organization of the United Nations (FAO) one-third of soils in the world are infertile due to unsustainable land-use management practices. In the mentioned report, it is also suggested that an improvement of soil health can be addressed by adopting specific management practices. One of the practices of greatest relevance to soils is increasing soil organic matter through the application of organic fertilizers, as compost, and targeted amendments, as biochar, in soils (EMRS, 2015).

1.2. Production and application of compost, a nutrient-rich soil amendment

Compost is an amendment that consists largely of decayed organic matter, generated in a process called composting, used for fertilizing and conditioning croplands. In the composting process, the main macromolecules in organic waste (carbohydrates, lignins, lipids and proteins) are decomposed by microorganisms,

releasing energy, CO_2, H_2O, NH_3 and other nutrients such as Ca, Mg, K and P. Environmental conditions such as air level, humidity, temperature, nutrient and macromolecules availability; and feedstock type determine the evolution of composting process as well as the characteristics and quality of the resulting material. As an example, compost from waste can come from two different trash cans: from organic waste and from residual waste. The compost coming from organic waste has better quality, since it contains less foreign materials.

1.2.1. Quality requirements of compost

Regardless the origin of the organic waste and the destination of the final product, indicative ranges can be established to assure minimum quality requirements of compost. These requirements consist of having an acceptable appearance and colour, proper sanitation, a good level of useful components for the soil, a certain constant in properties, and a very low level of impurities and contaminants.

In this last aspect it is important to consider the content of heavy metals (these will not be a problem in the composting of agricultural or livestock waste, while they will be in composting industrial, urban or activated sludge waste). If a compost with a high content of heavy metals is applied to the soil, it can be transferred to plants and groundwater. Both can be subsequently ingested by humans or animals with the consequent risk of disease. Table 1 and 2 show, respectively, the contaminant limit values and the minimum quality criteria of compost established by the European Compost Network.

Table 1. Contaminant limit levels established by the European Compost Network

Precautionary quality criteria	Parameter	Limit value
Hygiene	Salmonellae spp.	Absent in 25 g dry matter
Physical contaminants (Undesired ingredients and properties)	Impurities (glass, metal & plastics) > 2 mm	≤ 0.25 % dry matter
	Stones > 5 mm	< 4 % dry matter
	Weed seeds	≤ 1 seeds per litre
Inorganic pollutants (Potentially toxic elements)	Pb	130 mg/kg dry matter
	Cd	1.3 mg/kg dry matter
	Cr	60 mg/kg dry matter
	Cu	300 mg/kg dry matter
	Ni	40 mg/kg dry matter
	Hg	0.45 mg/kg dry matter
	Zn	600 mg/kg dry matter

Table 2. Minimum quality criteria established by the European Compost Network

Quality criteria	Parameter	Limit	Value
Chemical properties	Na^+	mg/L	≤ 250
	Cl^-	mg/L	≤ 750
Electrical Conductivity	Salinity / electrical conductivity	mS/m	≤ 190
Material properties	Organic matter	% DM	≥ 15 %
	Stability - Oxygen Uptake Rate (OUR)	mmol O_2 / kg OM / h	≤ 15
	Stability – Self heating test	Rottegrad index	V
	pH (H_2O) value	-	≥ 4 and ≤ 9
Plant response	Long term growth test with Chinese cabbage	Average Germination Rate (%), biomass production	≥ 80
	Short term growth test using cress	Germination rate (%)	≥ 80
		Index for root length development (%)	≥ 80

1.2.2. Benefits and problems of applying compost in soils

The application of compost has many advantages for soil quality:

- Improves chemical and biochemical properties of soil. Increase N and K content in an available form by roots and increase the plant available forms of P in soil.
- Incorporates microelements (Cu, Mg, Zn, Mn, Fe, B, etc.) that are needed for plant growth.
- Improves soil structure and macroporosity, reduces soil bulk density reducing the risk of soil erosion. Thus, it increases water retention capacity in sandy soils and prevent water saturation in clayed soils by improving soil drainage. This helps also with root penetration and growth.
- Increases the microbial action and, consequently, favours the degradation of residual applied herbicides and other phytosanitary products. This action also produces hormone-like products, growth regulators and promoters of the vital functions of plants.

In addition, in composting, the principle of the three R's is perfectly fulfilled: it reduces the amount of waste that must be dumped, reuses organic matter, and recycles nutrients to the soil where the compost is applied (NRAES, 1992; CWMI, 2007).

On the contrary, composting process and compost application generates gas emissions that can cause a secondary environmental impact (air and water pollution). Also, as above mentioned, the bad quality of compost could contaminate soils and groundwater.

1.3. Use of biochar as soil amendment

Biochar is a stable solid obtained from the pyrolisis of biomass. In more technical terms, biochar is produced by thermal decomposition of organic material (biomass such as wood, manure or leaves) under limited supply of oxygen and at relatively low temperatures (<700ºC). This material is used as soil amendment (International Biochar Initiative, 2018).

The production and application of this amendment is not a recent discovery, it begun thousands of years ago in Amazon Basin. Indigenous people used to place cooking fires that buried in soil resulted on a high content of black charcoal that improved their unfertile soils and created islands of rich fertile soils, called Terra Preta (Glaser, 2001; International Biochar Iniciative, 2018). During XIX century, this process was also done in Catalonia where was called, in catalan, boïc or formiguer (Enciclopèdia.cat). Boïc consists on burning the branches and shrubs cut from around the field and, then, throwing soil into the fire to drown it, causing an oxygen-limited environment in an earth kiln, and finally, scattering the remains in the field (IEC, 2007).

1.3.1. Evolution and current situation of pyrolysis systems

After hundreds of years using earth kilns for biochar production, in the late eighteen century, brick kilns were developed in an attempt to make the production more efficient. This type of kiln allows the capture of waste products as wood tar and pyroligneous acid and can still be found in Brazil and North America. Then, in the nineteenth century the portable metal ring kiln was developed by providing a relatively small-scale option and better transportation efficiencies by doing the process in-situ, but the efficiency was still similar to the earth kiln. Also in the nineteenth century, the technology of metal retorts was developed by combining the advantages of a better efficiency and considerably less pollution. Currently, new portable versions of metal retorts are available and, together with Kon-tiki biochar kiln, are the more used nowadays (Oaks, 2018). The production

capacity of these three kiln types makes them more indicated for small productions, encouraging circular economy, than for industrial productions.

The retort works by heating the wood in a separate chamber from the combustion, but the two chambers are linked so that when the wood reaches a sufficiently high temperature (270ºC), the volatiles are released and piped back into the combustion chamber, creating the heat source to continue the burn. With combustion ending only when the volatiles are gone (at 450ºC), the resultant product is very good quality. Burning off this wood gas reduces kiln emissions, releasing less smoke into the atmosphere (Oaks, 2018).

Figure 1. Retort from IDÀRIA, SCCL

The most recent innovation, Kon-tiki biochar kiln was developed from cone-shape pits found in South America. While most of the biochar produced during the last 5000 years was produced with open fire, modern pyrolysis systems, as retorts, suppress the fire. The Kon-tiki flame curtain kiln re-connects the carbonisation and the flaming of the pyrolysis gases and combines it with smart design based on modern thermodynamics to produce high quality biochar with low emissions. One of the main benefits of this pyrolysis system is that small-diameter waste wood can be burned and, unlike retorts, it can be filled during the biochar production until it is full of biochar. Another remarkable benefit is the high temperature (around 640ºC in the surface and 750ºC in 40 cm into the blaze zone) that leaves very few volatiles and maximizes the porosity of the resulting product. The last step of the production process is to quench the biochar, usually with clean water, to activate the biochar by increasing surface area, decreasing condensates and providing a limited-oxygen environment. Some research

studies point on using all type of liquid fertilizer to charge the hot char (Oaks, 2018; Ithaka Institute).

Figure 2. Kon-tiki kiln (Biochar Project Australia, 2016).

Pyrolysis conditions and feedstock types clearly affect physico-chemical properties of the product, such as the amount of carbon, nitrogen, potassium, calcium; surface area, porosity, aromaticity, and pH, among others. These variations in biochar characteristics would have significant implications on its application in soils (Oliveira 2017, Chen 2019) as will be explained in the following section.

1.3.2. Properties of biochar and its benefits as soil amendment

Previous experiences have pointed out the positive impacts of biochar when used in soils due to its structure, mainly in the case of low fertile soils. The main physical and physicochemical properties of biochar are large specific surface area, porosity, cation exchange capacity and water holding capacity. These favourable properties lead to an improvement in soil health and plant growth (Sanchez-Monedero, 2018). Specifically, the agronomic benefits of biochar application are: enhancement of nutrient availability by reducing its leaching through the soil (Laird, 2008; Schulz, 2012); decrease of soil bulk density, increasing of microbial activity, water saving, improvement of drainage, aireation and root penetration among others (International Biochar Iniciative, 2018).

Recently, some studies pointed out on the synergy between biochar and compost. Mixing biochar with compost seems a great strategy, since biochar is not a fertilizer in itself so compost can provide nutrients while the biochar can reduce its leachability (International Biochar Initiative, 2018). The joint application of compost and biochar

depends on many variables and may have effects that need to be studied. Specifically, when biochar is added to biomass before the composting process, the resulting material is called co-composted biochar.

1.4. Sustainability and climate change

In addition to the above mentioned improvements in soil health, biochar application can effectively mitigate climate change by soil organic carbon sequestration, a net removal of C and storage in soil relative to atmospheric CO_2 must occur and persist for several hundred years to a few millennia (Lorenz and Lai, 2014) due to its resistance to microbial degradation. Moreover, the application of compost and biochar contributes to circular economy by transforming biomass waste into resources.

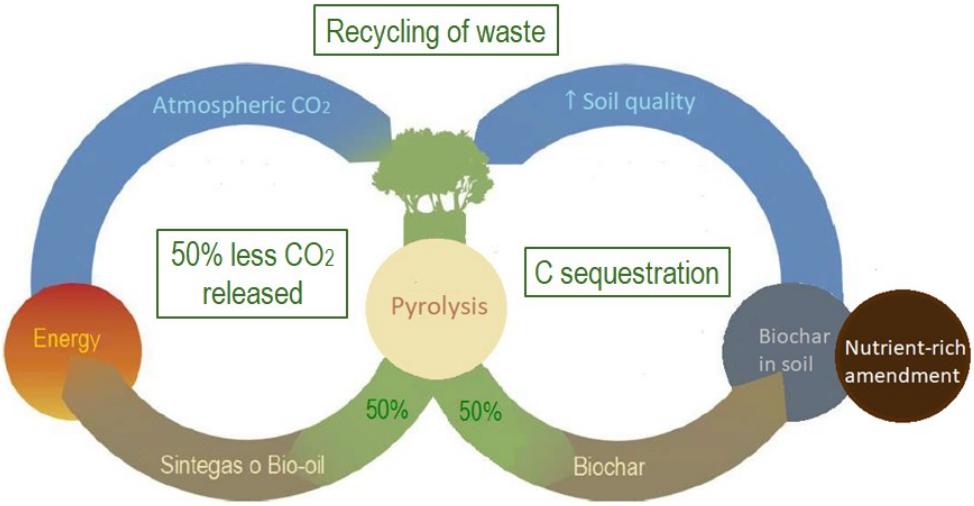

Figure 3. Cycle of biochar

To sum up, the use of biochar and compost as soil amendment positively contributes to Sustainable Development Goals (SDGs), specifically to SGD 15 "Life on land" and SGD 13 "Climate Action".

2. OBJECTIVES

The main objective of this project is to evaluate the benefits of applying co-composted biochar as amendment to agricultural soils to improve soil quality and crop growth. To achieve this general goal, the following specific objectives will be addressed:

- To compile experiences from the literature in terms of co-compost application in agricultural soils and the benefits this entails in soil improvement and plant yield.

- To identify those aspects of co-composting and co-compost application in soils that are not completely resolved and to propose future experiments to contribute to solve them.

3. LITERATURE SEARCH AND DATA EXTRACTION

3.1. Literature search

A systematic literature search was conducted through the Elsevier Science Direct, Web of Science and Scopus databases using the keyword "composted biochar" in the title, abstract, and keywords. The search was not limited to a certain timespan or region. From the amount of the identified sources, some studies were excluded according to two criteria: 1) studies that only discussed the impact of biochar use on the composting process were not included because they did not provide any information about the application to soil and its effect in soil quality and plant growth, 2) publications that focused on mixing compost and biochar directly in soils and not before composting were not included either since the scope of this paper is co-composted biochar. A total of 19 worldwide articles were carefully reviewed. The oldest paper reviewed was published in 2013 while the newest one was published in 2020.

The following data was extracted from the identified studies to assess the effect of co-composted biochar on plant growth and soil quality: 1) biochar type (feedstock, pyrolysis T, BET surface area), 2) compost type (feedstock, composting time), 3) plant type, 4) treatments application rate (different treatments were: control, biochar, compost, compost-biochar mixed directly in soils, not before composting, and co-

composted biochar), 5) scale 6) soil type, 7) soil pH and 8) location. This information is shown in Table 3. In our study, control refers to soil or soil + fertilizer, and treatment means control + co-composted biochar (COMBI).

3.2. Experimental conditions

Reviewed articles used different experimental conditions, but some conditions were more common than other. Biochar and compost feedstock varied greatly as the goal of its production is to reuse waste, so feedstock depends on what type of biomass is available. Nevertheless, the most common used feedstocks in biochar production were forest wood residues, green cuttings, willow wood and wheat straw, and the most used composted materials were: animal manure (chicken, cow...) and green cuttings. Regarding biochar, pyrolysis temperature was quite variable between 350 and 750 ºC, being 550 ºC the most common pyrolysis temperature. Regarding compost, the time of the composting process was also variable between 3 and 15 weeks. Different plant types were used in the reviewed articles, but the most common types were cereals as maize, wheat and oat.

One of the most important conditions to evaluate the effect of COMBI in plants and soil is co-composted biochar application rate. In the reviewed studies, COMBI application rate varied between 10 and 250 t/ha, being 25-50 t/ha the most common rate. In addition, percentage of biochar in co-composted biochar was in the range between 3 and 75%, with typical values between 10 and 15%. Different studies compared the effect of co-composted biochar with other treatments. In the wide majority, these treatments were soil, biochar alone, compost alone, and biochar and compost added separately in soils, after composting. In addition, seven of twenty studies added fertilizers in all treatments.

Finally, almost all studies were developed in fields rather than in lab. Experiments were located in places around the world (Australia, Ethiopia, Pakistan, Germany, China, Laos, Switzerland, Czech Republic and USA) and using many different types of soil (sandy, loamy, acidic, red, etc).

Table 3. Experimental conditions of the reviewed studies

#	Biochar (feedstock, pyrolysis T, BET surface area)	Compost (feedstock, composting time)	Plant type	Control	Biochar dose	Compost dose	Biochar + Compost dose (in situ)	COMBI application rate	Scale	Soil type	Soil pH	Location	Reference
1	Willow wood (550°C for 5-7h, BET: 332 m2/g)	Green waste, Bagasse, Chicken manure	Peanut	Fertilizer (F)	10 t/ha + F	25 t/ha + F	2.5 t/ha Biochar + 25 t/ha Compost + F	25 t/ha (9% biochar v/v) + F	Field	Red Ferrosol	5.9	Mareeba, north Queensland, Australia	Agegnehu et al. 2015
2	Willow wood (550°C for 5–7h)	Green waste, Bagasse, Chicken manure	Maize	Fertilizer (F)	10 t/ha + F	25 t/ha + F	2.5 t/ha Biochar + 25 t/ha Compost + F	25 t/ha (9% biochar v/v) + F	Field	Red Ferrosol	5.35	Tolga, north Queensland, Australia	Agegnehu et al. 2016a
3	Acacia (350-450ºC for 6 days)	Manure, dairy cattle feed leftovers, bedding (15 weeks)	Barley	Without amendment	10 t/ha	10 t/ha	10 t/ha Com + 2 t/ha B	10 t/ha (1:5 biochar:compost d.w.)	Field	Eutric Nitisol	4.97 and 4.83	Ethiopia	Agegnehu et al. 2016b
4	Willow wood (550°C for 5–7h)	Green waste, Bagasse, Chicken manure (98 days)	Banana, papaya	Fertilizer (F)	10 t/ha + F	25 t/ha + F	-	25 t/ha (9% biochar v/v) + F	Field	Red clay	5.89	north Queensland, Australia	Bass et al. 2016
5	Urban biochar: digested sludge from biosolids (650ºC)	95% Food waste (coffee, fruit peel and vegetables) and 5% sawdust (75 days)	Sorghum plants	-	10%	10%	-	10% COMBI (equivalent to 1% biochar)	Field	Sandy	5.2	Melbourne	Bhatta Kaudal et al. 2018
6	Green cuttings (650ºC)	Straw, draff, horse manure, maize silage, loam, stone powder (45 days)	Maize	Fertilizer (F)	1 Mg/ha i 40 Mg/ha + F	200 kg N/ha	-	200 kg N/ha + 10 Mg/ha B	Field	Sandy Cambisol	7.5	Gorleben, Northern Germany	Glaser et al. 2014
7	Forest wood residues (>700ºC)	Green cuttings, garden debris	Poplar, willow, alder	Without amendment	-	30 Mg/ha	-	30 t/ha (15% and 30% biochar v/v)	Field	Luvic Stagnosol	6.5	Rheinbach, Germany	von Glisczynski et al. 2016a

#	Biochar (feedstock, pyrolysis T, BET surface area)	Compost (feedstock, composting time)	Plant type	Control	Biochar dose	Compost dose	Biochar + Compost dose (in situ)	COMBI application rate	Scale	Soil type	Soil pH	Location	Reference
8	Forest wood residues (>700ºC)	Green cuttings, garden debris	Braeburn tree	Without amendment and with fertilizer	-	-	-	3kg per tree (15% and 30% biochar v/v)	Field	Luvic Stagnosol	6.5	Rheinbach, Germany	von Glisczynski et al. 2016b
9	Wood chips (80% coniferous, 20% deciduous wood) (700ºC for 36h)	Cow, horse, poultry manure (60 days)	Quinoa	Without biochar	2% w/w	-	-	2% w/w (11% biochar v/v)	Lab	Sandy, loam, sand, gravel	-	Germany	Kamman et al. 2015
10	Wheat straw (350-550ºC)	Poultry manure (6 weeks)	Wheat	Fertilizer (F)	-	-	-	12 t/ha (75% biochar v/v) + 12 t/ha pyroligneous solution	Field	Moderately salt stressed Antisol	8.25	Henan, China	Lashari et al. 2013
11	Wheat straw (480ºC)	Poultry manure (6 weeks)	Maize	Fertilizer (F)	-	-	-	12 t/ha (75% biochar v/v) + 12 t/ha pyroligneous solution	Field	Aqui-Entisol	8.25	Henan, China	Lashari et al. 2014
12	Peanut shell (350ºC for 2h)	Seafood shell powder peanut shell, comercial humate, inorganic nutrients (30 days)	Halophyte (sesbania and seashore mallow)	Without amendment	-	-	-	1.5% w/w, 5% w/w 10% w/w (50% biochar w/w)	Lab	Coastal	7.98	Yellow River Delta, China	Luo et al. 2016
13	Rice husk (14,5h)	Cow manure, clay (3 weeks)	Maize	Without amendment	10 t/ha	4 t/ha	10 t/ha B + 4 t/ha C	10 t/ha (50% biochar w/w)	Field	Gleyic Acrisol	4.2 and 5.4	central Laos	Mekuria et al. 2014

#	Biochar (feedstock, pyrolysis T, BET surface area)	Compost (feedstock, composting time)	Plant type	Control	Biochar dose	Compost dose	Biochar + Compost dose (in situ)	COMBI application rate	Scale	Soil type	Soil pH	Location	Reference
14	Garden peat (450ºC)	Farm manure (2.5 months)	Wheat	Without amendment (with half or full fertilizer)	-	-	-	2% w/w (0%, 25%, 50%, 75%, 100% biochar)	Lab	Alkaline	8.29	-	Qayyum et al. 2017
15	80% hardwood 20% coniferous wood chips (750ºC for 36h, BET: 144m2/g)	Green waste (8 weeks)	Grape	Without amendment	8 t/ha	55 t/ha	-	63 t/ha (20% biochar v/v, or 8t biochar/ha)	Field	Haplic regosol	7.9	Ayent, Valais, Switzerland	Schmidt et al. 2014
16	Beechwood (350-450ºC for 6 days)	Sewage sludge, freshly chaffed lop, soil (8 weeks)	Oat	Without amendment	-	50, 100 and 200 t/ha	-	50,100 and 200 t/ha (5-50% biochar)	Lab	Washed sand, loamy soil	6.3 and 6.4	Germany	Schulz et al. 2013
17	Activated carbon from a commercial producer (BET: 1200 m^2/g)	50% sewage sludge 35% chopped wood 15% rest soil or woody debris	Oat	-	-	10, 50, 100, 150 and 250 Mg/ha	-	10, 50, 100, 150 and 250 Mg/ha (3, 5 and 10 kg/Mg w/w biochar)	Field	A sandy and a loamy soil	8.54 and 7.21	Germany	Schulz et al. 2014
18	Soft wood (500-600ºC 6h)	Small sticks of maple and oak and green material (16 weeks)	L. perenne and E. Sativa	Without amendment	-	ratio 1:2 (w/w) to soil	ratio 1:2 (w/w) to soil (4 and 10%wt of biochar)	ratio 1:2 (w/w) to soil (4 and 10%wt of biochar)	Lab	Litavka	5.9	Czech Republic	Teodoro et al. 2020
19	Rice hull, low temperature	Chicken manure	-	Without amendment	1% biochar (B)	4% (3:7 of hardwood sawdust: chicken manure)		5% (2:7:1 of biochar: hardwood sawdust: chicken manure)	Lab	Tarboro loamy sand and Wickham sandy loam	6.5	Goldsboro, North Carolina, USA	Yuan et al. 2017b

3.3. Soil and plant parameters assessed

In the reviewed articles, the most studied parameters were soil organic carbon content, soil pH, greenhouse gases (GHG) fluxes, soil water content, cation exchange capacity, plant and grain yield and plant nutrient uptake. Table 4 shows which parameters were studied in each article.

Table 4. Reviewed parameters (SOC: Soil organic carbon, SWHC: Soil water holding capacity, CEC: Cation exchange capacity, GHG: greenhouse gases)

#	SOC	SWHC	CEC	pH	GHG fluxes	Plant nutrient uptake	Plant and grain yield	Reference
1	X	X	X	X	X	X	X	Agegnehu et al. 2015
2	X	X	X	X	X		X	Agegnehu et al. 2016a
3						X	X	Agegnehu et al. 2016b
4	X	X	X	X	X		X	Bass et al. 2016
5		X	X	X	X	X		Bhatta Kaudal et al. 2018
6		X		X		X	X	Glaser et al. 2014
7	X	X	X	X				von Glisczynski et al. 2016a
8							X	von Glisczynski et al. 2016b
9		X						Kamman et al. 2015
10	X		X	X			X	Lashari et al. 2013
11							X	Lashari et al. 2014
12	X		X	X				Luo et al. 2016
13	X		X	X		X	X	Mekuria et al. 2014
14	X						X	Qayyum et al. 2017
15						X		Schmidt et al. 2014
16	X			X				Schulz et al. 2013
17	X			X			X	Schulz et al. 2014
18		X				X		Teodoro et al. 2020
19	X			X	X			Yuan et al. 2017b

4. EFFECT OF CO-COMPOSTED BIOCHAR IN SOIL QUALITY

4.1. Effect in soil organic carbon

Soil organic carbon (SOC) is an indicator of soil organic matter content (SOM) (Agegnehu, 2015), which is the key parameter that influences soil quality and mitigates global warming by C sequestration (Von Glisczynski, 2016a). Soil organic matter is vital for sustainable yields as it improves soil structure, enhances the amount of soil nutrients, water retention capacity of the soil and provides substrate for soil microbial

biomass. This microbial biomass in turn makes nutrients more easily available for plants. These improvements result in an improvement in plant production. (Agegnehu, 2015; Agegnehu, 2016a; Bashir, 2020; Schulz, 2013). Compost and biochar are both organic amendments that, according to literature, improve soil organic carbon when applied to the soil.

In the current project, eleven articles were reviewed to analyse the effect of applying co-composted biochar into soils. All reviewed articles presented the same trend, a significant increase of SOM in COMBI-amended soils. Four of the reviewed articles (Agegnehu et al. (2016a), von Glisczynski et al. (2016a), Luo et al. (2016) and Quayyum et al. (2017)) studied changes in SOM by applying co-composted biochar with different doses of biochar. These four articles presented that SOM was increased when biochar dose in co-composted biochar was higher. Finally, Agegnehu et al. (2016a) also studied the long-term sequestration potencial which was of 0.62 t C per ton of biochar added.

Yuan et al. (2017b) justified the fact that co-composted biochar effects were more substancial than compost alone by explaining that co-composted biochar contained greater and more stable organic C that comes from biochar. Biochar resists biological degradation and consequently enhance soil carbon sequestration. Furthermore, despite that biochar stability varied with pyrolysis material and conditions, the average residence time of biochar in soil ranges from several years to decades. So the interaction between these materials results in rendering organic C more stable during composting by stimulating the stabilization of organic material.

4.2. Effect in soil water holding capacity

Soil water holding capacity (SWHC) expresses the total amount of water that can be stored in soil. This parameter represents the maximum capacity of porosities to hold water. SWHC is related to other parameters that are studied in some of the reviewed studies. These studied parameters are available water holding capacity (AWHC), available water content (AWC) and easily available water content (EAWC). An increase of any of these parameters results in an increase in soil water holding capacity.

As it was commented in the previous section, the higher the soil organic matter content, the higher the soil water holding capacity. The most important physical characteristic for improving soil water content (SWC) is porosity. Porous materials, as biochar, can storage water in their micro and macro porosities, reducing the amount of leaching and leaving water more plant-available (Glaser, 2014). Soil type is also an influent parameter of soil permeability and, consequently, of soil water holding capacity.

Seven articles were reviewed in order to assess the effect in soil water content of applying co-composted biochar as amendment in soils. The wide majority of reviewed articles presented a significant increase in soil water content when adding co-composted biochar. Agegnehu et al. (2015) and Agegnehu et al. (2016) observed an increase of soil water content of 24 and 14.6%, respectively when adding co-composted biochar in a Red Ferrosol soil with pH around 5.5. Glaser et al. (2014) and Kamman et al. (2015), which determined SWHC, showed an increase of around 15% when adding COMBI in a sandy soil. The increase of SWC with the addition of COMBI was justified by Glaser et al. (2014) with the fact that lowering bulk density results in increasing soil porosity, which consequently results in a higher retention of water, as explained previously. This fact is especially useful for soils with low water holding capacity, such as sandy soils in combination with high precipitation followed by longer drought periods, as the ones studied in Glaser et al. (2014). Then, Bhatta Kaudal et al. (2018) determined that AWHC increased in a 13% in soils when applying COMBI as amendment in a sandy soil with pH of 5.2. Bass et al. (2016) presented two different results in two different sites: Hu and Ho trials, both Red Ferrosols soils with a pH of 5.9. Hu trial followed the trend of the other reviewed articles; its results presented a significant increase in soil water content. Ho trial presented no differences in the average soil volumetric water content between treatments. And finally, Teodoro et al. (2020) presented as a result of COMBI application an increase of 30% in AWC, and 26% in EAWC (Figure 4).

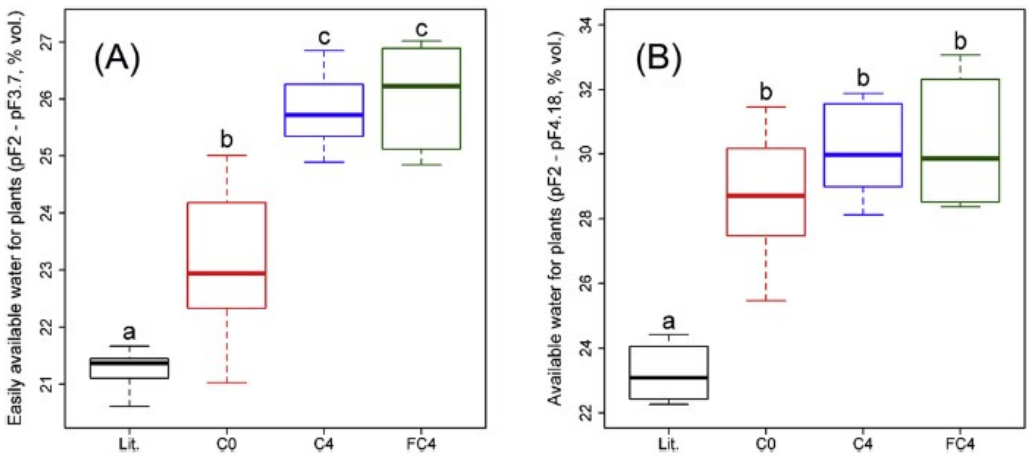

Figure 4. Boxplot of easily available soil water for plants (A) and available soil water for plants (B): Lit – control; C0 – compost and C4 – co-compost with 10% biochar; FC4 – compost + 4% biochar mixed directly in soils, not before composting (Teodoro, 2020)

According to Teodoro et al. (2020), the increase of easy-available water when adding biochar and compost can also be explained by a swelling effect, a loading of H_2O molecules on the biochar surface through the hydrogen bonds. This suggests that the amount of strongly bonded water increased in the compost treatment from 2% to 6%, by the application of biochar in composting. Conversely, both biochar and compost treatments alone increased the amount only by 2%. This means that biochar presence in compost enhanced mainly the amount of water ranging between field capacity and the drought stress zone. Thus, the application of compost-biochar mixture could be beneficial for plants during periods of agricultural drought.

To sum up, a significant increase in soil water content was observed in almost all the articles reviewed.

4.3. Effect in cation exchange capacity

Cation exchange capacity (CEC) is a measure of negatively charged sites on the surface, which hold positively charged ions and nutrients such as Na, K, Ca, Mg and Zn. Soils with low CEC often present low fertility and vulnerability to soil acidification, as CEC and SOC content increase the buffering capacity of a soil. There are also some reported studies which suggest that the enhanced CEC increased soil fertility by increasing nutrient availability through nutrient retention in soil instead of leaching through soil profile out of the rooting zone (Agegnehu, 2016a). For these reasons, to ensure a good soil quality and production it is important to get a high or medium CEC.

One of the ways to achieve a high CEC is by adding biochar as soil amendment, as it presents high surface area with functional groups that can be sites of cation exchange. This effect of increasing CEC is more pronounced in soils with low CEC, as sandy soils. Carboxyl groups of charcoal surface are known to increase over time due to chemical and biotic oxidation and hence resulting in the very high CEC (Bhatta Kaudal, 2018). And also, according to Agegnehu et al. (2015), biochar is not only a soil conditioner that increases CEC but may act as a fertilizer itself. Because some biochar contains ash and so adds nutrients such as K, Ca and Mg to the soil solution, increasing the pH of the soil and providing readily available nutrients for plant growth.

In our study, eight articles were reviewed to assess the effect of co-composted biochar when applied into soils. In six studies (Agegnehu et al. (2015), Agegnehu et al. (2016a), Bass et al. (2016), Bhatta Kaudal et al. (2018), von Glisczynski et al. (2016a), Luo et al. (2016)) the application of co-composted biochar results in a significant increase of CEC in the range between 15.7% and 37%. Mekuria et al. (2014) also presented an increasing trend but it was not significant as the other six studies. Finally, Lashari et al. (2013) did not present any change when adding co-composted biochar.

Bhatta Kaudal et al. (2018) found consistent this increase in CEC with the increase in carboxyl functional groups in biochar. This study believes that the organic acids produced during the composting of food waste may have helped to oxidize the surface of the material. This oxidation increased the CEC which led to trapping of ammonium and other cations.

Von Glisczynski et al. (2016a) conclude that in his study, CEC was only elevated significantly when 32.5 Mg/ha of compost was combined with the highest amount of biochar (20 Mg/ha). Appearing, therefore, that the increase of soil CEC was produced by biochar rather than by compost. However, the degree of this CEC rise depends on soil properties, because infertile soils usually are most sensitive to biochar additions. This justification was consistent by the fact that Mekuria et al. (2014) and Lashari et al. (2013), the only articles that not presented a significant increase in CEC when adding COMBI, were also the ones that applied the lowest amount of co-composted biochar in soil, 10 and 12 t/ha, respectively.

To finish, Luo et al. (2016) suggests that an increase of CEC results in a decrease of soil pH. The commented study also suggested that when increasing CEC with co-

composted biochar, the absorption of cations as K^+, Ca^{2+} and Mg^{2+} by plants is promoted, resulting in an H^+ release to compensate charge balance and consequently, in a decrease of soil pH. This mechanism can have a global impact in soil pH when initial soil is slightly acid and with low CEC.

4.4. Effect in pH

Soils can be classified according to their pH value. Soil with pH between 6.5 and 7.5 are considered neutral, while when pH is over 7.5 is considered alkaline and when pH is less than 6.5 is considered acidic (soils with pH less than 5.5 are considered strongly acidic). Soil pH affects the solubility of nutrients and chemical compounds in soil water, and therefore the amount of nutrients available to plants. Some nutrients are more available under acid conditions (low pH) while others are more available under alkaline conditions (high pH). For example, soils with pH around 8.5 presents low availability of Fe and P, as at this pH these elements are present in precipitated forms. Another example is that soils with pH below 4.5 present Al in a toxic form for plants, Al^{3+}. However, the wide majority of mineral nutrients are readily available to plants when soil pH is near neutral, between 5.5 and 7.5. Some amendments as compost and biochar can produce changes in soil pH and consequently increase or reduce the availability of nutrients for plant uptake (Queensland Government, 2013).

To analyse the effect of the addition of co-composted biochar in soil pH, twelve studies were reviewed.

On one hand, Schulz et al. (2014), Glaser et al. (2014) and von Glisczynski et al. (2016a) presented similar results that show a significant increase of 0.4-1.2 units of soil pH when co-composted biochar (pH=8.4-8.6) is applied. These three studies were developed in sandy and loamy soils with pH-values between 6.5 and 8.5. Also, Glaser et al. (2014) and von Glisczynski et al. (2016a) studied the evolution of pH by measuring it at two points of the experiment. Both studies presented that in the second point pH values declined in all plots but the increase, in relation to control, was still significant when applying co-composted biochar. Figure 5 presents Agegnehu et al. (2016a) results by showing pH values of different treatments: control, compost, COMBI with 15% of biochar and COMBI with 30% of biochar; in the 3 studied years (from 2012 to 2014).

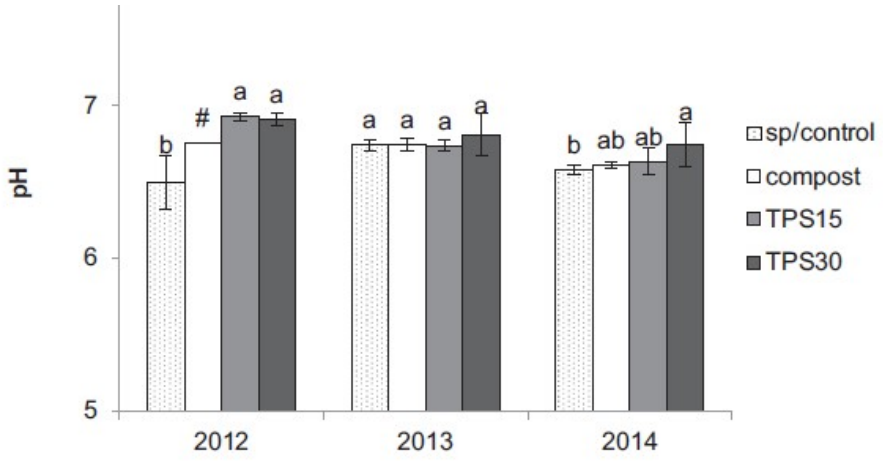

Figure 5. Soil pH-values in the control, the compost, the biochar–compost containing 15% biochar (TPS15), and the biochar–compost containing 30% biochar (TPS30)-treated soils (von Glisczynski, 2016a). Different letters indicate differences among treatments.

Von Glisczynski et al. (2016a) justified this variation among different years as a seasonal variation that may be promoted by alternating redox cycling at the site under study.

There were also three studies that showed an increasing trend but without significant differences between treatments: Agegnehu et al. (2015), Agegnehu et al. (2016a) and Bass et al. (2016). These three studies were carried out in similar soils, red clay soil with pH in a range between 5.35 and 5.9. Bass et al. (2016) justified the absence of a significant increase in soil pH under COMBI treatment by the low application rates of biochar, coupled to the counteracting effect of the lower compost pH than biochar, 7.5 and 8.1, respectively. Agegnehu et al. (2015) justified the obtained results by the limited liming capacity of the biochar used in the study.

On the other hand, there were three studies that showed a significant reduction of 0.11 - 0.5 units of soil pH when co-composted biochar (pH=7.5-8.43) was applied to soils: Luo et al. (2016), Lashari et al. (2013) and Yuan et al. (2017b). Two studies, Luo et al. (2016) and Lashari et al. (2013), were developed in salty soils with pH between 7.98 and 8.25, while Yuan et al. (2017b) was developed in a Tarboro loamy sand and a Wickham sandy loam with a pH-value of 6.5. Luo et al. (2016) justified this decrease by the H^+ release from the ion exchange between Ca^{2+} or Mg^{2+} in the coastal soil and the oxygen-containing functional groups on the biochar surface.

Also, Bhatta Kaudal et al. (2018) showed this decreasing tendency, but their results were not significant. Specifically, at the end of the experiment, co-composted biochar presented a soil pH value of 5.9.

The other two reviewed studies presented different trends among their own results. Mekuria et al. (2014) presented two different trials (Veunkham and Naphok sites). Results of Veunkham experiment showed that, in both first and second years, the application of composted biochar resulted in an increase in soil pH (from 4.1 to 4.4). In the first year of Naphok experiment, the application of composted biochar resulted in a non-significant reduction of soil pH (4.3 to 4.1). But in the second year, the application of composted biochar did not affect soil pH (4.3). In a similar way, Schulz et al. (2014) studied the application of composted biochar in two different types of soil, loam and sand. Composted biochar addition had no significant influence on pH in sandy soil substrate (soil pH = 8.3), while pH significantly increased in loamy soil substrate (soil pH = 7.4). Schulz et al. (2014) justified the fact that co-composted biochar had no significant effects on pH in sandy substrate with the fact that the composted biochar showed pH value which was similar to the pH value of the used soil substrate. But, surprisingly, in the loamy soil substrate where soil pH presented a significant increase with the addition of COMBI treatment, pH of both soil substrates was comparable, and the same composted biochar amount was added.

Another point to comment is that when comparing units of significant increase or decrease in soil pH it can be observed that studies presenting an increase, this increase are in a greater degree than the reduction degree of the studies that present a significant decrease in soil pH. Specifically, in the reviewed articles the increase in soil pH is in the range of 0.4-1.2 units of pH, while the decrease is between 0.11-0.5. Despite the commented variations, the vast majority of the reviewed articles presented soil pH-values in the correct balance range (5.5 – 7.5), only three studies presented values out of the range. Lashari et al. (2013) and Luo et al. (2016) presented pH-values higher than 7.5, but with the application of co-composted biochar this value was decreased from 8.3 to 8.0 and from 8.0 to 7.7, respectively, resulting in a value closest to the suitable range. On the other hand, Mekuria et al. (2014) presented pH-values lower than 5.5, but the application of treatment resulted in an increase, from 4.0 to 4.4, a value closest to the range.

4.5. Effect in greenhouse gases fluxes

Greenhouse gases (GHG) are gases that absorb and emit radiant energy within the thermal infrared range raising the planet temperature. The primary greenhouse gases in Earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). According to EPA (United States Environmental Protection Agency, human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years. And also, from 2018 greenhouse gas emissions, agriculture represented the 9,9%, being the main greenhouse gases in agriculture those related to C and N global cycles. The contribution of agricultural soils to CO_2 and N_2O emissions depends on the biophysical processes, and the incorporation/decomposition of organic residues in the soil (EPA US, 2020; Muñoz, 2010).

Natural sources of CO_2 emissions basically correspond to the respiration process of terrestrial organisms. But, on the other hand, C sequestration by soils can potentially serve as CO_2 sinks. Soils of the world can act as sinks or sources of GHG emissions, and the net balance between the absorbance of atmospheric C and its release determines the net temporal status of soils as either C absorbers (inputs) or releasers (outputs) (Muñoz, 2010). Moreover, as biochar and compost are organic materials, their application increase C content, what usually results in an increase of CO_2 emissions. It is important not to focus in absolute emissions and to compare the emissions with the amount of C added.

Agegnehu et al. (2015) and Yuan et al. (2017b) presented a significant reduction in CO_2 flux of 1.5 kg/(ha·hr) compared to control and 35% compared to compost treatment, respectively. The other studies (Agegnehu et al. (2016a) and Bass et al. (2016)) presented the opposite trend. Agegnehu et al. (2016a) and Bass et al. (2016) in observed a significant increase of 1500 and 4000 kg/(ha·season), respectively.

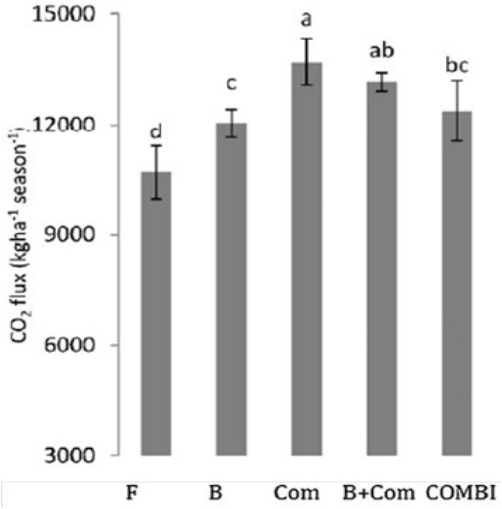

Figure 6. Average emissions of CO_2 over the whole growing season for each treatment (soil with fertilizer (F), soil with biochar (B), soil with compost (Com), soil with compost and biochar mixed in soil (B+Com) and soil with co-composted biochar (COMBI). Different letters indicate differences among treatments (Agegnehu, 2016a)

Figure 6 shows that compost application increase CO_2 emissions, but when mixed with biochar these emissions are reduced. This reduction is because biochar slows down the respiration process of organisms and it also retains gas in its porosities. The effect is more pronounced when compost and biochar are mixed for longer periods.

On the other hand, agricultural soils also emit N_2O. Different management practices on agricultural soils can increase the availability of nitrogen in the soil and result in an increase of emissions of nitrous oxide. Specific activities that contribute to N_2O emissions from agricultural lands include: the application of synthetic and organic N fertilizers, the growth of nitrogen-fixing crops, the poor drainage of organic soils, and irrigation practices (Muñoz, 2010).

On the other hand, almost all studies presented a decrease of N_2O emissions by applying co-composted biochar in soils. Agegnehu et al. (2015), Bass et al. (2016) and Bhatta Kaudal et al. (2018) presented a non-significant decrease, while Yuan et al. (2017b) reduced significantly N_2O emissions by 27% compared with compost treatment. Agegnehu et al. (2016a) was the only one that presented a significant increase, this was a little increase of 1 kg/(ha·season). Figure 7 shows Agegnehu et al. (2015) results, which suggests that the application of compost, biochar or its combination reduces N_2O emissions, being the non-treated plot the one presenting the highest N_2O emissions.

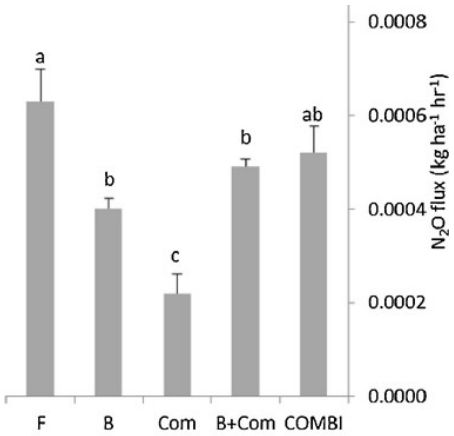

Figure 7. Average emissions of N_2O (kg/(ha·hr)) for each treatment (soil with fertilizer (F), soil with biochar (B), soil with compost (Com), soil with compost and biochar mixed in soil (B+Com) and soil with co-composted biochar (COMBI) (Agegnehu, 2015)

According to Yuan et al. (2017b), the reduction of soil N_2O emissions when COMBI is applied can be justified by controls on soil organic C stabilization and the activities of microbial functional groups, especially bacterial denitrifiers. Also, this study suggested a number of mechanisms for reduced N_2O emissions after biochar is applied to soil, such as increased aeration, reduced nitrate availability to denitrifiers, the toxic effect of PAH and phenolic compounds for microorganisms, sorption of ammonium by the biochar surface, improvement in soil moisture, increasing in soil pH and change in microbial community structure.

As it has been commented previously, the application of co-composted biochar does not present the same trend for different studies analysed. Yuan et al. 2017b explained this effect by the fact that both feedstock source and pyrolysis temperature can considerably affect the biochar bulk and surface properties. Moreover, differences in biochar properties may affect the direction and magnitude of soil greenhouse gas emissions. Yuan et al. 2017b exemplified this justification with the fact that biochar C:N ratio has little influence on soil greenhouse gas emissions, but feedstock source, pyrolysis temperature and biochar pH can significantly affect soil CO_2, CH_4, and N_2O fluxes after biochar amendment. Surprisingly, Agegnehu et al. (2015), Agegnehu et al. (2016a) and Bass et al. (2016) presented the same biochar feedstock, pyrolisis conditions and co-composted biochar application rate, but as it was commented each study presented different results.

However, in conclusion these results are about GHG emissions when co-composted biochar is applied into soil. But to accurately study the viability of this material as amendment, GHG emissions during its production needs to be studied, to determine GHG emissions during the whole life cycle of co-composted biochar.

5. EFFECT OF CO-COMPOSTED BIOCHAR IN PLANTS

5.1. Effect in plant nutrient uptake

Nutrients are one of the main variables on which plant growth depends. Specifically, plant growth and development depends on which nutrients are available in the soil and on which concentration are they. A deficiency of any of the essential nutrients may decrease plant productivity and consequently decrease the overall biodiversity. (Morgan, 2013).

There are two classes of nutrients that are considered essential for plants: macro and micronutrients. Macronutrients are all nutrients found in higher concentrations than 1%. These nutrients are crucial for cellular components like proteins and nucleic acids and they are required in large quantities. The most important macronutrients are N, P, S, Mg, Ca, Na and K. On the other hand, micronutrients are those nutrients found in lower concentrations than 1%, an excess of them can be toxic. Micronutrients often act as cofactors in enzyme activity. Some examples of micronutrients are Fe, Zn, Mn and Cu (Morgan, 2013).

Plants usually obtain mineral nutrients from the soil through plant roots, but the efficiency of this uptake depends on many. An important factor is soil chemical properties and composition, as certain soils does not contain nutrients or these nutrients are found in forms that are not available for plant uptake. Soil properties like pH as previously explained, soil water content and soil compaction may exacerbate these problems (Morgan, 2013). Some literature suggests that the application of organic amendments as compost or biochar could improve plant nutrient uptake.

In our study, the effect of co-composted biochar in nutrient uptake will be assessed by reviewing six articles. Four of these six articles presented the same trend, a

significant increase in nutrient uptake (N, P, K, Ca, Mg) when applying co-composted biochar in soils (Agegnehu, 2015; Agegnehu, 2016b; Bhatta Kaudal, 2018; Mekuria, 2014). Mekuria et al. (2014) justified this trend by improvements in soil chemical properties following the application of soil amendments. This argument is supported by the positive and significant relationships between total N, P, and K uptakes and soil pH, TOC, CEC, and exchangeable Ca^{2+}, and Mg^{2+} at both sites and cropping seasons.

Other two studies presented different trends for different nutrients. Glaser et al. (2014) presented results showing that the addition of biochar into composting process and the soil application of the resulting material increased P, K, Zn uptake, decreased Cd, Ni, Cu, Na uptake and did not present any change in Mg, N, Ca, Mn, Co, Cr and Pb uptake. According to Glaser et al. (2014), explanations for the discrepancies between their results and literature data might be the use of different plants and experimental setups. For example, one suggested factor could be that in their study co-composted biochar was mixed only to 15 cm soil depth while plant roots could reach 1m depth or even more, and in other studies pots were used in which the substrates were homogeneously mixed. Therefore, roots could be less affected by biochar due to the low incorporation depth.

Moreover, Teodoro et al. (2020) presented different results between the two plant types used. In *Lolium perenne* plot COMBI application presented an increase of K uptake, a decrease of S and Mn and no effect in Ca, Mg, Cu. In *Eruca Sativa* COMBI application resulted in an increase of Mg and S, and a decrease of K, Mn, Cu, Ca. Furthermore, all treatments decreased the availability of the target contaminants (Cd, Pb and Zn) in the soil, resulting in a decreased of the plant uptake (with the exception of Pb for *E. Sativa*).

5.2. Effect in crop yield

Crop yield is the measure of crop produced per area of land. It is important to increase this parameter to meet the growing demand for food without claiming more land from nature and to positively contribute to life on land.

To evaluate changes in plant and grain yield when applying co-composted biochar twelve articles were reviewed. Nine of these eleven articles suggested that the application of COMBI resulted in a significant increase of plant and grain yield in the

range between 13 and 195%. (Agegnehu, 2015; Agegnehu, 2016a; Agegnehu, 2016b; Glaser, 2014; Lashari, 2013; Lashari, 2014; Mekuria, 2014; Qayyum, 2017; Schulz, 2014).

Some studies observed that this increase was related to the increase in nutrient and water retention, plant available nutrients, biological N fixation (Agegnehu, 2015), soil moisture (Agegnehu, 2016a), soil pH, CEC, TOC, and exchangeable bases improvements (Mekuria, 2014). In the case of saline soils, Lashari et al. (2014) presented results that showed that the application of co-composted biochar caused a significant decrease in salt stress to, and thus growth improvement of, the maize crop. In detail, EC, Na^+ and Cl^-, as well-recognised indicators of soil salinity, were all reduced by over 30% in treated maize plots. Finally, Schulz et al. (2014) suggested that the increase could be attributed to the very low content of nutrients and organic matter in the pure sandy substrate where any low amendment would alter the conditions for plant growth.

On the other hand, there were two studies that presented different results. Von Glisczynski et al. (2016b) presented that fruit yield and quality were not affected by the application of COMBI amendment for apple orchards with fertile soils. Bass et al. (2016) presented that banana crop yield was reduced by 24% by COMBI addition and no significant effect was observed on the papaya crop yield. Bass et al. (2016) justified the obtained results in banana crop yield by a possible soil N (and K) retention in added biochar. If co-composted biochar presents restricting access to these nutrients this may result in reduced plant growth and, consequently, reduced crop yield. Though, Bass et al. (2016) supports that limited data make robust statistical conclusions impossible in this case. On the other hand, papaya crop yield, which presented an absence of a yield reduction effect when adding COMBI, was also justified. There are indications that the papaya plants may be utilizing the additional soil nutrients in other ways. The absence of a yield reduction effect on biochar-containing treatments in papaya crop yield does not support the hypothesis that biochar is limiting the access of nutrients to the plants, as suggested above in the discussion of banana crop yield analysis. Differences in the application procedure may be another possibility. At papaya field, amendments were comprehensively incorporated into the soil and had a generally lower particle size, in contrast to banana field where amendments were applied to the surface and not incorporated further. Some studies suggest that the additional layer of organic material

on the surface may limit the through-flow of fertilizer through to the deeper soil layers where the plant roots can access them. Further investigation is needed in order to verify this hypothesis and to study if the way of application is a critical aspect of the application of these amendments.

6. FUTURE EXPERIMENTS PROPOSAL

Several knowledge gaps with respect to the effect of the application of co-composted biochar in soil quality and plant growth have emerged from our literature review which are listed below. They highlight the key knowledge gaps that need to be addressed specifically to understand the effect of co-composted biochar when applied in different conditions as soil type, soil pH, location, amendment application rate, among others.

- To study in contrasted types of soils the effect of co-composted biochar application in soil water content during water stress situations.

- To study in different types of soils the effect of low doses of co-composted biochar in cation exchange capacity.

- To perform more studies applying co-composted biochar in soils with soil pH out of the range between 5.5 and 7.5 to determine changes in soil pH.

- To study CO_2 emissions during the whole life of co-composted biochar and to compare it with the emissions that biomass would release if it was not converted to this amendment.

- To perform systematic complete multifactorial studies to study the effect of several factors either alone or combined in soil quality and plant growth. Factors that needs more research in are soil type and the way the soil amendment is applied (homogeneously, with local application, with a certain application dose…)

Ideally, these further researches should be done by using residues produced near from the application field as feedstock to prepare compost or biochar in order to ensure that these processes maintains its goal to reuse a residue and to be sustainable. Moreover, to compare with other articles, it is recommended to use common conditions such as those discussed in section 3.2 and to evaluate the largest number of parameters among: soil

organic carbon, soil water content, cation exchange capacity, soil pH, GHG emissions, plant nutrient uptake and crop yield.

7. CONCLUSIONS

From this research study, the initial conclusion that can be drawn is that the effect of co-composted biochar in soils is multifactorial and it is difficult to extract unequivocal conclusions pointing in the same direction. Nevertheless, from the obtained results the following conclusions are drawn:

- There is a high amount of studies about applying compost mixed with biochar, but only a few quantity studying co-composted biochar and its effect when applied in soils. In our study, 19 articles from around the world and published between 2013 and 2020 were found.

- Experimental conditions of reviewed articles highly varied among others, what makes conclusions draw more difficult.

- The most studied parameters in reviewed articles were: soil organic content, soil water content, cation exchange capacity, soil pH, GHG emissions, plant nutrient uptake and crop yield.

- COMBI application in soils results in an increase of soil organic matter. Moreover, there are studies that suggest that biochar is the main responsible of this effect by adding more stable organic C.

- Soil water content was significantly increased by COMBI application in almost all the reviewed articles.

- Cation exchange capacity significantly increases with the application of COMBI at high doses. Studies that applied COMBI at low doses (10 and 12 t/ha) did not present significant changes in CEC.

- Observed effects in soil pH with COMBI application greatly varied with experimental conditions (pH and buffering capacity of soil and amendments).

However, it can be concluded that soil pH when applying COMBI is in the correct range between 5.5 and 7.5, or near this range.

- CO_2 emissions increased and decreased, regarding control, depending on the experimental conditions. However, to study CO_2 emissions accurately they have to be studied together with other emissions produced in the whole life of the material and compared with those emissions that biomass would have emit if was not converted into co-composted biochar. N_2O emissions were generally reduced by COMBI application in soils.

- Plant nutrient uptake was generally increased by COMBI addition in soils. However, unusual studies presented reductions in some nutrients which where associated to a non-homogeneous application of COMBI.

- Crop yield was generally increased by COMBI addition due to the increase in nutrient and water retention, plant available nutrients, biological N fixation, soil moisture, soil pH, CEC, TOC and exchangeable bases improvements.

- There are still several gaps that need to be studied about COMBI application conditions and effects. Specifically, future research needs to be done putting attention on conditions as soil type, soil pH and COMBI application rates.

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